CANADA'S CHALLENGE & OPPORTUNITY

Transformations for major reductions in GHG emissions






PROJET TROTTIER POUR L'AVENIR ÉNERGÉTIQUE

TROTTIER ENERGY FUTURES PROJECT

Trottier Energy Futures Project Partners

April 2016

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of the Trottier Family Foundation.

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Foreword

The Intergovernmental Panel on Climate Change (IPCC) 2014 Synthesis Report states that *"substantial [greenhouse gas] emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term, and contribute to climate-resilient pathways for sustainable development."*

The report suggests that there are multiple transformational pathways to attaining the goal of significantly reducing greenhouse gas (GHG) emissions.

The challenge of significantly reducing GHGs in Canada is complex, involving a number of combinations of possible pathways. To explore ways of achieving deep reductions, the Trottier Energy Futures Project is defined by the goal of reducing GHG emissions by 80 per cent from 1990 levels by the year 2050, and with consideration of reducing GHG emissions by 100 per cent or more by the end of the century. The Project employs a systems analysis approach by specifying a target reduction for GHG emissions from combustion sources. It uses two models to optimize pathways to attaining the target at minimum cost, for a variety of scenarios that define alternative futures. The approach defines the least-expensive ways forward and sets the stage for informed conversations that will increase understanding of GHG reduction options open to Canada, and the steps that will lead to early reductions.

The pathways outlined could be more economically attractive when the co-benefits are considered, such as improved public health, traffic management, and infrastructure life-cycle costs. An economic assessment of co-benefits and risks for each scenario was beyond the scope of this research.

Finally, this study is a collaborative effort by three organizations. We may have differing opinions about some of the pathways outlined, but we are in strong agreement that it is important to publish the results of the study in order to stimulate an informed discussion about how to meet internationally defined GHG reduction targets. We need to have those conversations as quickly as possible in order to create the future we desire.

Trottier Family Foundation

The Canadian Academy of Engineering

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Acknowledgements

The initiative and funding for the Trottier Energy Futures Project (TEFP) came from Lorne Trottier, through the Trottier Family Foundation. Lorne Trottier is an engineer, an entrepreneur, and a philanthropist. He is a Member of the Order of Canada and a Fellow of the Canadian Academy of Engineering. He is a proud Canadian and is committed, with his family, to being a catalyst for Canada to assume a leadership role in addressing the serious climate-change challenge in Canada and around the world.

The project was jointly sponsored by the Canadian Academy of Engineering (CAE) and the David Suzuki Foundation (DSF). Overall direction for the project was provided by a three-person Project Board, including John Leggat (CAE), Peter Robinson (DSF), and Lorne Trottier.

The Project Team included Oskar Sigvaldason, Project Manager and President, SCMS Global; Kathleen Vaillancourt, President, ESMIA Consultants; Michael Hoffman, President, whatIf?; Mara Kerry, Director of Science and Policy, DSF; Ian Bruce, Science and Policy Manager, DSF; and Kevin Goheen, Executive Director, CAE. Other principal contributors included Professor Warren Mabee, Queens University; Professor Emeritus Robert Evans, University of British Columbia; and Alex Boston, President, Boston Consulting. Professor Olivier Bahn, École des Hautes Études Commerciales de Montréal, was Advisor to ESMIA Consultants. Professor Patrick Condon, University of British Columbia, was Advisor to Boston Consulting. Valuable support was provided by Erik Frenette (ESMIA), and by Bas Straatman and Shona Weldon (whatIf?). A four-person Expert Review Panel provided quality assurance for the project. Members of the panel included Professor Andre Plourde, energy economist and Dean of Public Affairs, Carleton University; John Leggat, former Assistant Deputy Minister (Science & Technology), Department of National Defence; Ken Ogilvie, environmental policy consultant to governments, business and environmental organizations; and Professor Miguel Anjos, Canada Research Chair in Discrete Nonlinear Optimization, Polytechnique Montréal and GERAD.

During the course of the project, discussions were held and reviews were conducted with selected representatives from government, industry, non-profit organizations, and universities across Canada, including the National Energy Board, Natural Resources Canada (including the Canadian Forest Service), Environment Canada, Statistics Canada, Canadian Electricity Association, Canadian Association of Petroleum Producers, and Alberta Innovates — Energy and Environment Solutions.

Following preparation of the Draft Report, reviews were carried out by CAE and DSF. For CAE, reviews were done by a committee chaired by Professor Douglas Ruth that included Sara Jane Snook, Eddy Isaacs and Professor Aniruddha Gole. Reviews were conducted by Miles Richardson and Professor Peter Victor, Directors of the Board of DSF, and by Peter Robinson and Gideon Forman of DSF.

Executive summary

The Trottier Energy Futures Project is a comprehensive engineering analysis of Canada's future energy systems, with the goal of achieving an 80 per cent reduction in GHGs by 2050, relative to 1990 levels.

The study is based on two detailed quantitative models for combustion emissions that have been calibrated using historical data.

The models calculated projected GHG emissions in Canada from combustion to 2050 using a variety of scenarios, as well as a defined set of energy technologies. The models also calculated "marginal costs" for the projected energy system transformations in the form of equivalent carbon prices over time for each scenario.

For most scenarios, the approach was based on currently deployed technologies with plausible extrapolations for future improvements and cost reductions. Furthermore, the simulations assumed a centralized power generation and distribution system similar to the dominant paradigm of today.

Several potential technologies that could make contributions to reducing GHG emissions were not explored due to insufficient data.

The main value of this project is that it shows what is possible with current technology. While the precision of the predicted emission levels is limited by the accuracy of the models and the underlying assumptions, an analytical approach involving several scenarios has produced robust results that identify promising pathways and options for deep GHG reductions in Canada.

Findings

The most aggressive scenario occurs with lower global fossil-fuel demand and correspondingly lower production and export by Canada. This scenario results in a 70 per cent reduction in combustion emissions, from 425 million tonnes (MT) in 1990 to 128 MT in 2050. Very large increases in electricity and biomass/biofuels use occur as a result.

The aggressive scenario includes proven technologies, such as hydro, nuclear and wind power, as well as technologies that are not yet commercially available, such as second-generation biofuels, coal-fired thermal power plants retrofitted with carbon capture and storage, and bioenergy production with carbon capture and storage. In addition, the model selects 122 gigawatts of new large-scale hydro power. Significant reductions in emissions occur in all five end-use sectors, and rapid decarbonization of electricity supply also occurs (by 2030). In 2050, the three sectors still producing significant GHG emissions include transportation, industry, and fossil-fuel supply.

A qualitative assessment was made of the potential for reducing GHG emissions from non-combustion sources. The most optimistic projection for the combination of combustion and non-combustion sources indicates GHG emissions of 360 MT in 2050, which is greater than the goal of 118 MT. Net-negative emissions may be required to close the gap.

The adoption of significant energy conservation and efficiency measures offers low-cost options (including several at negative cost) for reducing GHG emissions. For example, energy conservation measures eliminate a large proportion of the future demand for space heating in the commercial sector — as much as 60 per cent in 2050, depending on the scenario (and as much as 40 per cent in the residential sector).

The modeling derives marginal cost per tonne of CO_2-equivalent for imposed GHG emission limits. These costs depend on the scenario analyzed but generally exceed $100 per tonne of CO_2-equivalent in the early years for all scenarios and increase over time to several hundred dollars per tonne (2011 dollars).

Priorities for action

The project highlights the changes in Canada's existing and future energy infrastructure that will be needed in order to achieve deep GHG reductions. Promising pathways to a low-carbon future are identified. And while future technologies and other innovations may lead to new pathways or result in lower costs than those shown by the analysis, the project demonstrates that substantial progress can be made by 2030 using currently available systems to reduce GHG emissions. Key areas include significantly increasing the supply of electricity and biomass/biofuels in order to displace fossil fuels in all five end-use sectors, decarbonizing electricity production by switching to non-emitting sources, enabling transfers of electricity between provinces and territories, and implementing a comprehensive program of energy conservation and efficiency measures. In addition, as several provinces and the federal government have already committed to implementing carbon pricing, a national climate strategy, along with regulations and incentives that support innovative GHG-reduction technologies and initiatives, may be within reach.

Challenges

As the project progressed, a number of significant challenges became apparent. If these challenges remain unaddressed, achieving deep reductions in GHG emissions will prove exceedingly difficult. Further investigation and assessment are needed in the following areas:

- The development and deployment of second-generation biofuels, especially for use in heavy freight and rail transport
- In-depth analysis of options for reducing GHG emissions from industrial combustion and non-combustion sources
- A comprehensive program of data collection and analysis to assess the full magnitude of the fugitive emissions problem and to identify mitigation approaches
- Accelerated research on ways to reduce GHG emissions from oil and natural gas production, upgrading, and refining, including fuel switching and process changes

- Further work on the extent to which improved urban form can reduce overall infrastructure costs and related GHG emissions, and on promising GHG reduction approaches, such as public transit, co-generation, distributed generation, district heating, waste to energy, and local energy storage

- Research on ways to achieve net-negative GHG emissions, including biomass electricity generation with carbon capture and storage, increased use of wood products for carbon retention in buildings, and carbon sequestration through afforestation and reforestation

- Recognition that consultations with decision makers, communities, and First Nations will need to occur for the envisioned pathways to come to pass

Concluding comments

The Trottier Energy Futures Project provides a rigorous comprehensive analysis of the potential for deep reductions in Canadian GHG emissions. It identifies promising and implementable low-GHG reductions options and pathways. The deep reduction pathways are highly challenging and involve extensive energy conservation and efficiency measures, major restructuring of our energy infrastructure, deployment of promising but not yet commercially available technologies, and fundamental changes in how people think about and use energy.

The energy options that must be implemented to achieve deep GHG reductions (reduced use of fossil fuels for end uses, decarbonization of the electricity supply, increasing the use of biomass/biofuels) all result in developments between now and 2050 that present formidable challenges.

The results from the project cast considerable doubt about the timely availability of technology and associated infrastructure; however, the greatest challenge may not be technical or even economic as much as political and social/cultural. Deep GHG reductions will affect all Canadians and will therefore necessarily involve changes in lifestyle. The results also speak to a requirement for carbon pricing and supporting regulation. The accomplishment of the societal transformations involved in reducing GHG emissions by 80 per cent or more will require leadership from all sectors of society, and will require Canadians to develop a widely shared vision of low-carbon lifestyles and energy systems.

The results of the project can be used to inform national dialogue on strategies needed to achieve deep emission reductions. Our future will be determined by the choices we make today about energy use and GHG emissions. The open and frank discussion this project engenders can lead to meaningful progress and build confidence that Canada can work internally and with other nations to restore the health and resiliency of the planet's climate system.

Project summary

1. Context and setting

1.1 Project goals

The primary goal of this project is to assess options and pathways for reducing greenhouse gas (GHG) emissions in Canada by 80 per cent by 2050, relative to the 1990 level. Total GHG emissions in 1990 were 589 million tonnes (MT), which results in a goal of 118 MT for 2050.

As stated in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the longer-term global goal is to achieve stabilization of CO_2 concentrations in the atmosphere (currently just above 400 parts per million) at about 450 ppm "to avoid a rise in temperature that exceeds 2 degrees Centigrade above pre-industrial levels." This will require net emissions for the entire world to be reduced to zero (or beyond) by 2100. The IPCC'S call for action was endorsed in the Leaders' Declaration at the G7 Summit in June 2015.

This project is a comprehensive engineering analysis of future energy systems, with the goal of achieving an 80 per cent reduction in GHGs by 2050, relative to the 1990 level. The study is based on two detailed quantitative models for combustion emissions that have been calibrated using historical data. The models were used in a complementary fashion (i.e., outputs from one model provided important inputs to the other model) as well as for cross-checking the end results of each. This methodology increased both the scope and the robustness of the results.

The models calculated projected GHG emissions in Canada from combustion to 2050 using a variety of scenarios, as well as a defined set of energy technologies. The models also calculated "marginal costs" for the projected energy system transformations in the form of equivalent carbon prices over time for each scenario.

For most scenarios, the approach was based on currently deployed technologies with plausible extrapolations for future improvements and cost reductions. Due to the constraints of time and readily available modelling data, the simulations assumed a centralized power generation and distribution system similar to the dominant paradigm of today. For the same reasons, only limited changes in urban form were evaluated.

Several potential technologies that could make contributions to reducing GHG emissions were not explored due to insufficient data. Examples of such technologies include incremental hydro, advanced batteries, compressed air energy storage, recyclable metal powder fuels, bioengineered biofuels, and so on.

The main value of this initial project is to show what is possible with currently known technology. Furthermore, the precision of the predicted emission levels is limited by the accuracy of the models and the underlying assumptions. The analytical approach involving the study of several scenarios, however, has produced robust results that identify promising pathways and options for deep GHG reduction in Canada.

1.2 GHG emissions in Canada

GHG emissions for 1990 and 2010, as reported in Canada's annual National Inventory Reports, are shown in Figures 1 and 2. Emissions come from the combustion of fossil fuels and from non-combustion sources. The relative percentages from these sources were 72 per cent and 28 per cent for both 1990 and 2010 (i.e., there was no significant change in the proportion of total emissions they each represented).

Combustion emissions

GHG emissions from the combustion of fossil fuels result from three main purposes: meeting domestic end uses (residential, commercial, transportation, industrial, and agriculture); generating electricity (mostly from coal and natural gas), which also serves domestic end uses; and producing and transporting coal, oil and natural gas for export.

For domestic end uses in 1990, 74 per cent of the energy supplied came directly from fossil fuels and their derivatives, 22 per cent from electricity, and four per cent from biomass and biofuels. Of the 74 per cent, approximately 85 per cent of the emissions resulted from "consumption" (e.g., burning natural gas, burning gasoline in cars) and 15 per cent from the "production" supply chain (extracting, collecting, upgrading, refining, transporting, and distributing fossil fuels to end-users).

In 2010, combustion emissions equalled 503 MT, which as noted above was 72 per cent of total GHG emissions. This included 369 MT (73 per cent of combustion emissions) for directly meeting end uses, 101 MT (20 per cent of combustion emissions) for electricity production, and 33 MT (seven per cent of combustion emissions) for production and transport of oil, natural gas, and coal for export.

Non-combustion emissions

Non-combustion emissions (shown separately in Figures 1 and 2) come from four sources: industrial processes, agricultural processes, fugitive releases and waste.

- Industrial-process emissions (eight per cent of Canada's total GHG emissions in 2010) mostly come from chemical reaction processes that emit GHGs as by-products. They occur predominantly in Canada's cement, iron and steel, aluminum, chemical, petrochemical, electrical utility, and semiconductor industries.

- Fugitive emissions (nine per cent) come from the intentional or unintentional release of GHGs from production, processing, storage and delivery of fossil fuels. In particular, fugitive emissions include venting and flaring of GHGs at facilities that process natural gas and oil.

- Agricultural-sector emissions (eight per cent) come from enteric fermentation, which produces methane from digestive processes in animals, and manure management, which results in GHG emissions from animal waste. In addition, agricultural soils emit nitrous

GHG emissions in Canada (1990)

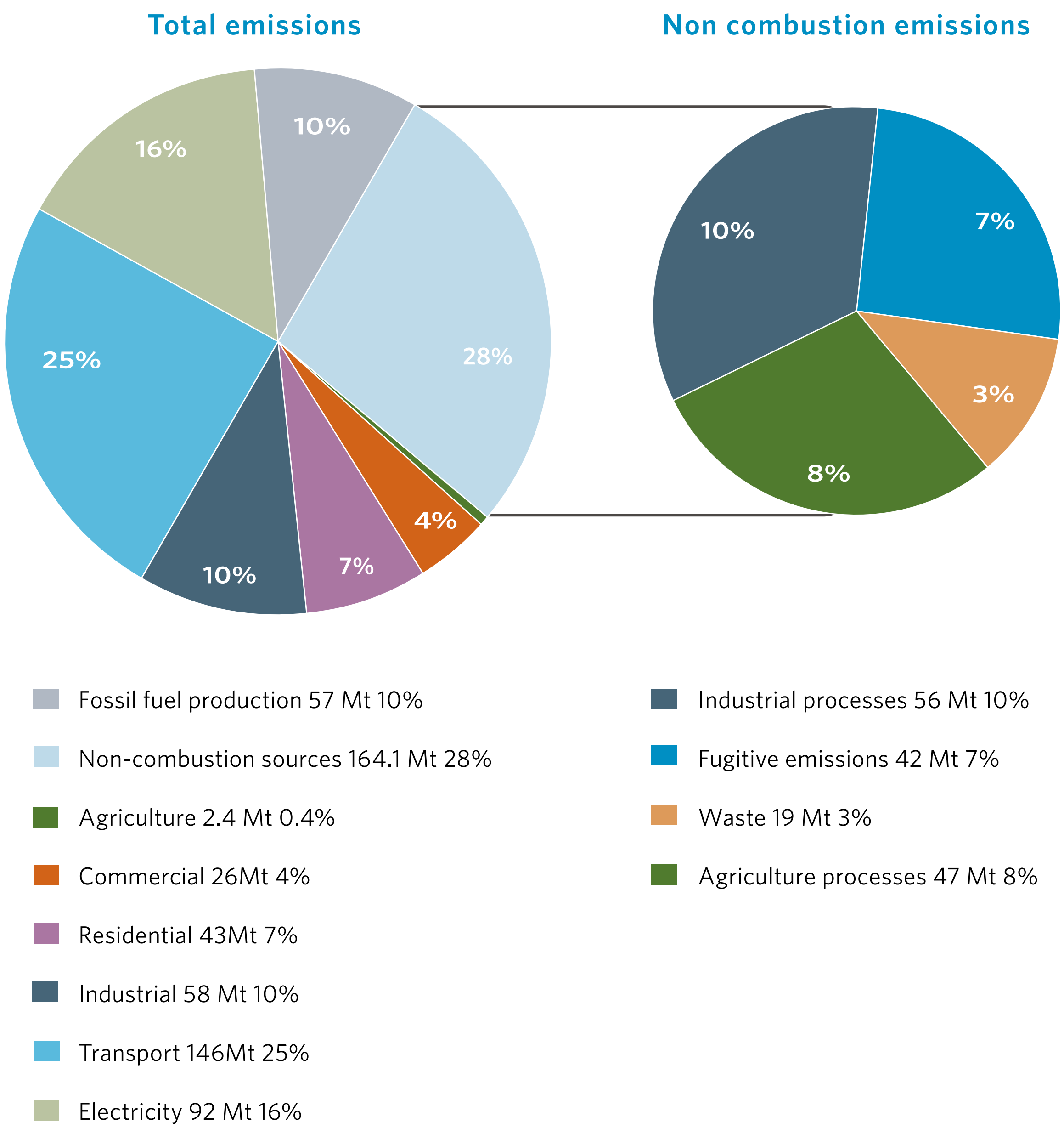


Figure 1. GHG emissions in Canada (1990): 589 MT

GHG emissions in Canada (2010)

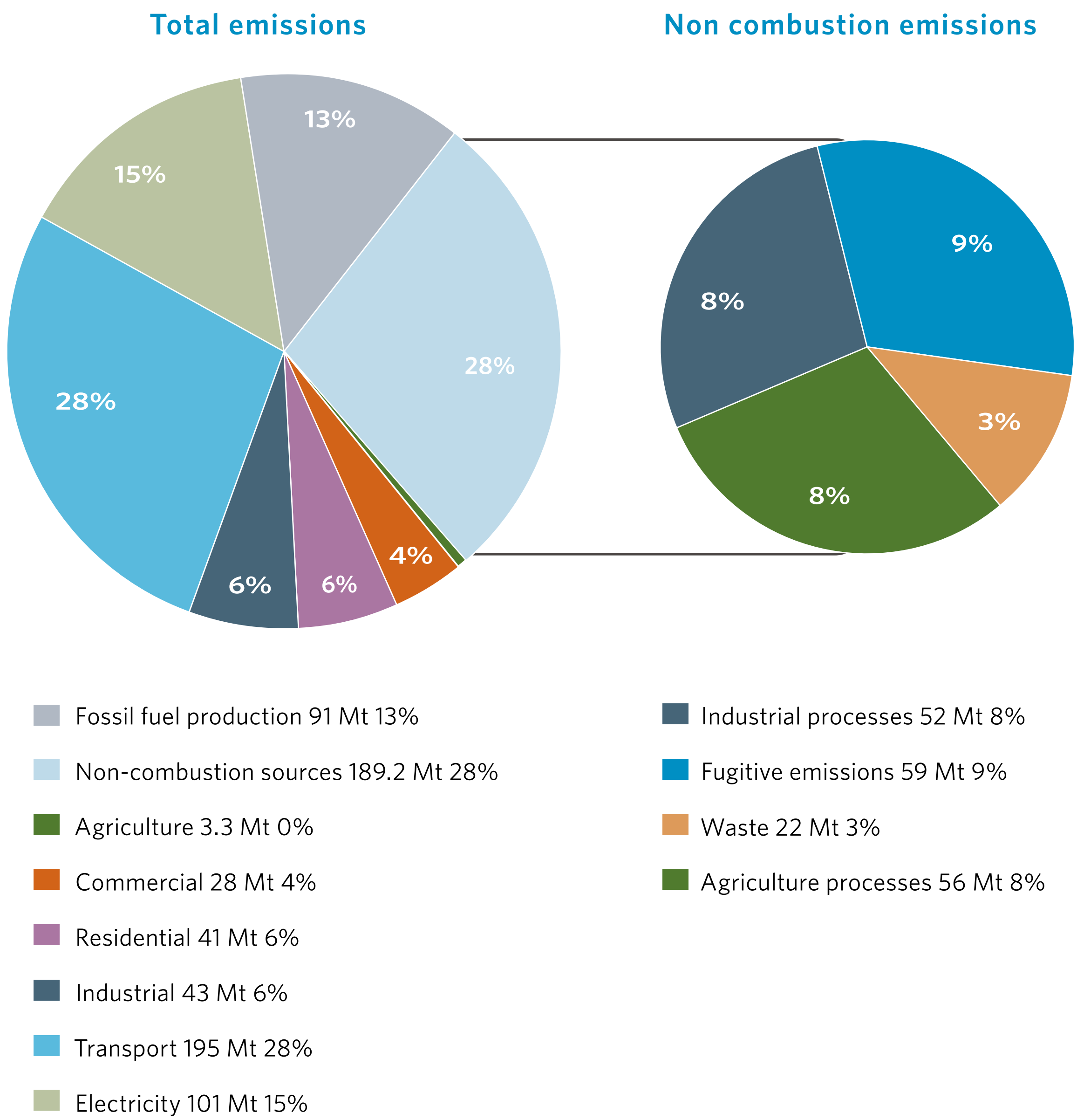


Figure 2. GHG emissions in Canada (2010): 692 MT

oxide from the application of nitrogen-based fertilizers and from crop residue decomposition.

- Waste-sector emissions (three per cent) come mostly from solid waste disposal on land, waste water treatment, and waste incineration. The dominant type of emission is methane from municipal landfill sites.

1.3 Project approach and premises

The main focus of the analysis in the project was reducing GHG emissions from combustion sources.

The principal options for reducing combustion emissions include the following:

- Energy conservation and energy efficiency
- Reducing fossil fuel use through conversion to increased use of electricity and biomass/biofuels
- Decarbonizing the electricity supply with non-GHG-emitting generating sources, including hydro, nuclear, wind, solar, biomass/biofuels, geothermal, and fossil-fuel-fired generation with carbon capture, use and storage (CCUS)
- Implementing process changes to reduce use of fossil fuels, especially in industry and for fossil fuel production, upgrading and refining

The overall approach for the project consisted of three sets of activities:

i. Application of two complementary mathematical models to provide a rigorous analytical basis for deriving minimum-cost solutions for meeting prescribed reductions in combustion emissions for 11 separate future scenarios

ii. Carrying out comprehensive reviews of transformation options with associated costs for reducing emissions over time in every sector and jurisdiction across Canada

iii. Analysis of 11 future GHG emissions reduction scenarios

This process has resulted in observations that provide valuable perspectives on Canada's GHG reduction challenge (Section 2), defining priorities for immediate action (Section 3) and selecting priority areas for further investigation and assessment (Section 4).

Mathematical models

Two models were selected to analyze alternative representations of the future and to select transformation strategies and related investments for achieving deep reductions in combustion emissions for all of Canada:

- The North American TIMES Energy Model (NATEM) — a proprietary optimization model developed and maintained by ESMIA Consultants. NATEM includes a Canadian version of the TIMES/MARKAL family of optimization models, supported by the International Energy Agency

- The Canadian Energy System Simulation (CanESS) model — a proprietary simulation model developed and maintained by whatIf? Technologies.

The two models were used in combination as well as independently for the project. They provided different insights into the behaviour of Canada's large and complex energy systems. The NATEM model performed the bulk of the computations for detailed scenario analysis, while the CanESS model provided economic and socioeconomic projections for Canada, supported energy system definitions, validated parameters to be used, and performed extensive background testing and verification to ensure that the results from the project were consistent and credible.

In the NATEM model, Canada is represented by its 13 interconnected provincial and territorial jurisdictions. Analysis is carried out over nine time periods, between 2011 and 2050. The model represents the entire energy system for each jurisdiction, including extraction, collection, processing, transport, distribution, end uses and trading of energy commodities. At every location where combustion emissions are produced, transformation options, with associated costs, are defined for reducing such emissions. End use demands are specified in terms of needs (e.g., transportation is expressed in vehicle-kilometres) over a future time horizon. Profiles of reductions in emissions between 2011 and 2050 are prescribed. Based on this, the model systematically searches through all possible combinations of options, including transformations, for meeting both prescribed time-varying demands and reduced emissions at "minimum overall cost." Minimum overall cost is defined as the "minimum present-worth system cost," which is evaluated by discounting all future investment and operating costs to equivalent 2011 dollars.

The CanESS model has similar representations for all of Canada and for the energy system in each respective jurisdiction. It computes system responses on a year-to-year basis for prescribed combinations of end-use demands and emission reductions.

The CanESS model was calibrated with data for the 1978 to 2010 period from the Canadian socio-economic information management system (CANSIM). With this information and with projections from the National Energy Board (NEB) and Statistics Canada, the model was used to project population growth, gross domestic product (GDP) per capita, total GDP, and industrial gross output to 2050.

The CanESS model was also used to define important inputs for the NATEM model, including the following:

- Deriving optimal dispatch representations for electricity supply for different combinations of generation supply, including large-scale hydro, "run-of-river" hydro, nuclear, coal- and natural-gas-fired generation, intermittent renewables (wind, solar), pumped storage generation, and system interconnections. Results of such representations were provided as input for the NATEM model.

- Assessing "capacity factors" for existing wind generation in jurisdictions across Canada, and projecting future "capacity factors" with improved design and siting

- Conducting assessments of projected "capacity factors" for large-scale solar generation for grid supply in jurisdictions across Canada

- Defining inputs for modified end-use demands arising from improved "urban form" (e.g., changes to urban growth patterns, urban densification, and increased public transportation)

- National assessment of transformation opportunities and limitations for increased production of biomass and biofuels for meeting expanding needs for these fuels to replace fossil fuels

In addition to incorporating the above-noted considerations into the CanESS model for transfer to the NATEM model, two additional representations were incorporated directly into the NATEM model:

- Dependable capacity — to ensure that the sum of guaranteed capacity contributions for each class of electricity generating facilities was equal to or greater than the system peak demand, especially for intermittent renewable generating sources, such as wind, solar, and run-of-river hydro power generation.

- Differential electricity grid development costs — to ensure that high-voltage transmission grids were developed in parallel with the changing composition of electricity generation supply, especially for intermittent renewable energy sources, which required increased investments in the grid.

Extensive testing and calibration of both models was done before initiating model runs for the various scenarios.

Transformation options and costs

The approach to the analysis ensured that transformation options for reducing emissions were based on the best information available. The study projects that the standard of living in Canada will increase between now and 2050 and that industrial output will double during this period.

Each of the end-use sectors was analyzed in terms of options for both meeting growing demands and reducing combustion emissions. These included conservation, energy efficiency, and various transformation options, such as building new infrastructure and retrofitting existing infrastructure. Costs included both investment and operating costs.

A similar approach was used to define transformation options and associated costs for energy supply and the associated supply chain, from primary energy source to delivery point. Working papers were prepared on Electricity Supply and Delivery, Fossil Fuels, Oil Sands, Carbon Capture and Storage, Transport of Fossil Fuels, Biomass, and Biofuels.

A special assessment was carried out on opportunities for reducing emissions with improved urban form. This was based on defining a long-term vision for transformation of urban regions in Canada and assessing corresponding opportunities for reducing emissions between now and 2050.

Costs used in the NATEM model were based on the best available information from reputable sources, both in Canada and elsewhere. Representative sources included Canada's National Energy Board, the Canadian Electricity Association, the Energy Information Administration and the National Renewable Energy Laboratory (NREL) in the U.S. Department of Energy, and the Energy Technology Systems Analysis Program (ETSAP) in the International Energy Agency. In select cases, cost information was reviewed with external sources and modified to reflect special situations in Canada, such as increased costs in remote regions.

Transformation options, which included technologies that are not yet commercially proven, were selected based on the best available information. The general guideline was to adopt a "conservative" approach in choosing projected performance and associated costs for such options.

Estimates for the time required to build and commission infrastructure and facilities were included; however, there was no accounting of the time required for any development to proceed, related to economic, socioeconomic, environmental, jurisdictional, and political constraints, as well as First Nations considerations. The premise was that infrastructure projects would come on-line when they were required by the model to be in service. As such, there was an implicit assumption that all approvals would be in place.

Limited data availability and other information gaps resulted in the analysis being less rigorous for non-combustion emission sources, which accounted for 28 per cent of total Canadian GHG emissions in 2010. Literature reviews and expert consultations were used to estimate potential GHG emission reductions for these sources.

Scenario analysis

The models are used to analyze 11 separate scenarios. Eight of the scenarios involve high fossil fuel production and assume no constraints on the export of fossil fuels, while three low fossil fuel production scenarios assume lower demand for Canadian energy exports and a proportionate reduction in fossil fuel consumption based on concerted global action to reduce GHG emissions. The first scenario is a reference scenario in which Canada takes no additional measures targeted at reducing GHGs. All subsequent scenarios (except Scenario 1a) incorporate targets for GHG reductions by 2050 that start at 30 per cent and increase to 60 per cent (and in one scenario 70 per cent). Seven high fossil fuel production scenarios explore options for reducing GHG emissions, starting with proven technologies and adding promising but not yet commercial ones, such as second-generation biofuels and carbon capture, use and storage. One of these scenarios assumes no new nuclear generating capacity is installed, beyond existing planned refurbishments. Six of the seven scenarios assume there are no barriers to interjurisdictional sharing of electricity among the 10 provinces and three territories. The three low fossil fuel production scenarios include results from reduced use of fossil fuels in Canada and reduced export, based on the premise that there are corresponding worldwide reductions in the use of fossil fuels.

Summary descriptions for the 11 scenarios (several of which have sub-scenarios for increasing targets of GHG reduction, as noted below) are as follows:

- **Scenario 1:** Reference (or Baseline) Scenario, based on no targeted reductions in GHG emissions
- **Scenario 1a:** Modified Reference Scenario, based on no targeted reductions in GHG emissions, but including low (i.e., reduced) fossil fuel production and export
- **Scenario 2:** Targeted Reductions in GHG Emissions (30 per cent to 60 per cent by 2050), with no additional high-voltage interconnections between jurisdictions
- **Scenario 3:** Targeted Reductions in GHG Emissions (30 per cent to 60 per cent by 2050), adding high-voltage interconnections between jurisdictions
- **Scenario 3a:** Targeted Reductions in GHG Emissions (30 per cent to 60 per cent by 2050), including low fossil fuel production and export, and adding high-voltage interconnections between jurisdictions
- **Scenario 4:** Modified Scenario 3, including improved urban form
- **Scenario 5:** Modified Scenario 3, including second-generation biofuels and carbon capture, use and storage (CCUS)
- **Scenario 6:** Modified Scenario 3, including additional electricity exports to the U.S.
- **Scenario 7:** Modified Scenario 3, with no new nuclear power generation (beyond planned refurbishments)
- **Scenario 8:** Modified Scenario 5, adding bioenergy with CCS (BECCS) and biojet fuel, and removing the moratorium on new large-scale hydro power in B.C.
- **Scenario 8a:** Modified Scenario 8 (30 per cent to 70 per cent reductions), including low (i.e., reduced) fossil fuel production and export

Eleven Scenarios (S1-S8 and S1a, S3a and S8a)

Premises included in scenarios	High fossil fuel production/export								Low fossil fuel production/ export		
	S1	S2	S3	S4	S5	S6	S7	S8	S1a	S3a	S8a
No targeted reductions in GHG emissions	X								X		
Targeted reductions in GHG emissions		X	X	X	X	X	X	X		X	X
No new high-voltage interconnections	X	X							X		
New high-voltage interconnections added			X	X	X	X	X	X		X	X
Changes in urban form added				X							
Second-generation biofuels added					X			X			X
Carbon capture, use and storage (CCUS) added					X			X			X
Increased electricity exports to U.S. added						X					
New nuclear power generation added	X	X	X	X	X	X		X	X	X	X
No new nuclear power generation, other than retrofits to existing plants							X				
Biojet fuel added								X			X
Bioenergy with CCS (BECCS) added								X			X
New large-scale hydro in B.C. added								X			X

2. Results of scenario analysis

Results for the Reference Scenario, projected to 2050, are shown in Figure 3. These results can be compared with the results for 1990 and 2010, as shown in Figures 1 and 2.

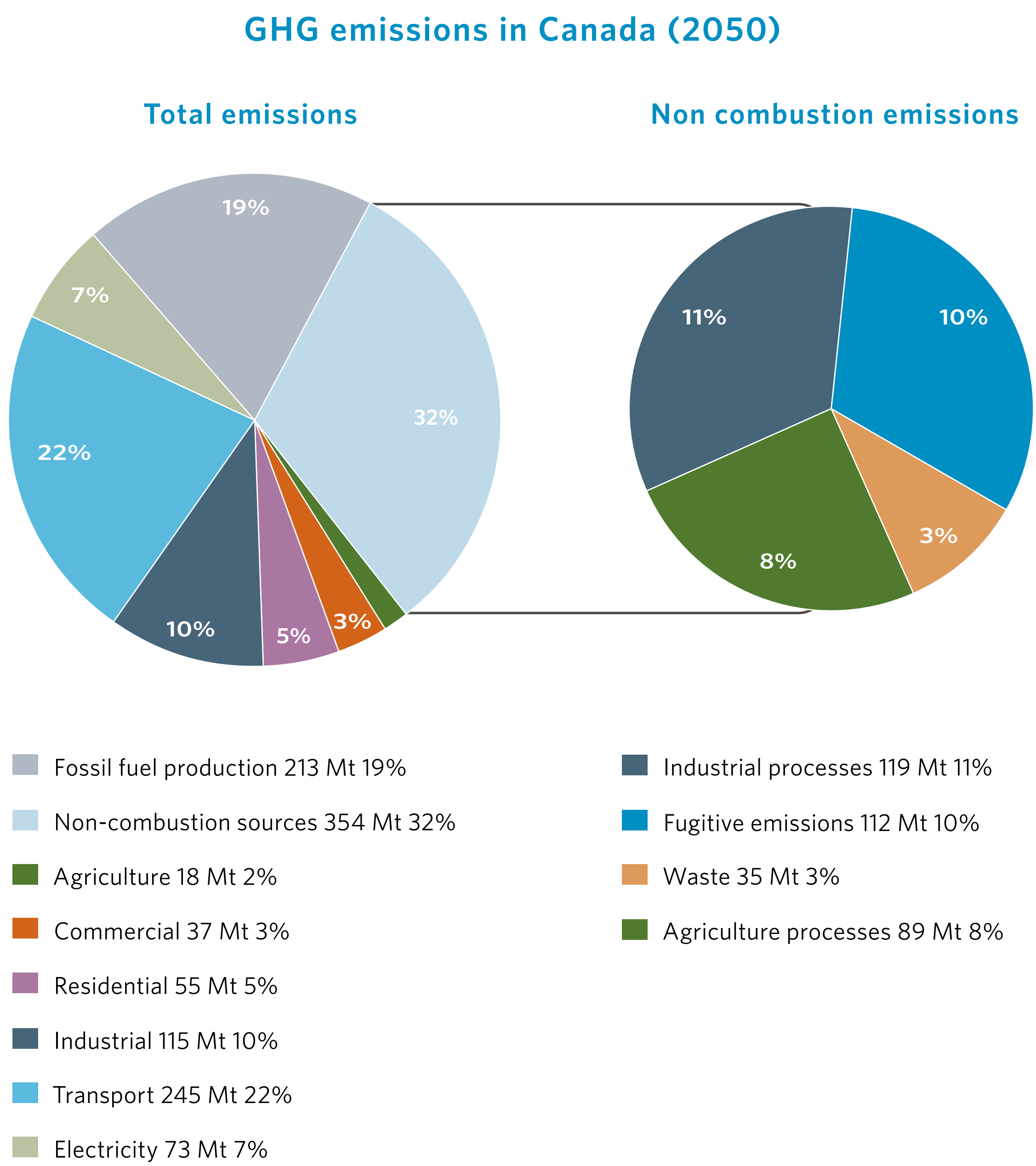


Figure 3: Projected GHG emissions in Canada in 2050 — Reference Scenario: 1109 MT

Reference scenario

The Reference Scenario projections for 2050 show continuing growth of energy demand in all sectors, with no major shifts in the roles of fossil fuels, electricity, and biomass/biofuels for meeting end uses. Significant changes are observed in the transportation sector for passenger and freight transport, with passenger-transport energy use declining due to tighter fuel-economy standards (CAFÉ), while rapid growth in freight transport leads to large increases in diesel use. Overall, GHG emissions increase from the 2010 level of 692 MT to 1109 MT by 2050, dominated by transportation, industry, and fossil fuel production. Non-combustion emissions increase from 28 per cent to 32 per cent of total GHG emissions (i.e., from 189 MT to 354 MT), primarily related to increased fugitive releases from increased fossil fuel production.

Longer-term results

Findings arising from the model-based analysis are shown in Figures 4, 5, and 6. These figures include the results from the largest computed reduction in GHG emissions (i.e., Scenario 8a). For this scenario, there is a 70 per cent reduction in combustion emissions, from the 1990 level of 425 MT to 128 MT in 2050. This is 83 per cent below the 755 MT of combustion emissions in 2050 for the Reference Scenario (see Figure 3). The emissions reduction is due to significantly lower use of fossil fuels and correspondingly large increases in the use of both electricity and biomass/biofuels. Scenario 8a includes lower assumed global fossil fuel demand and therefore lower Canadian fossil fuel production and export. The scenario includes proven technologies for generation supply, such as hydro, nuclear and wind power. Technologies that are not yet commercially viable, such as second-generation biofuels, coal-fired thermal power plants retrofitted with carbon capture and storage, and bioenergy production with carbon capture and storage, are also included. In addition, the model selects 122 gigawatts of new large-scale hydro power.

Additional information on the results for Scenario 8a is shown in Figure 6. Some observations of interest:

i. There are progressive reductions in emissions in all five end-use sectors (residential, commercial, transportation, industrial and agricultural) for the entire period from 2011 to 2050.

ii. There is a rapid decarbonization of electricity supply, with this sector being essentially fully decarbonized by 2030.

iii. By 2050, three sectors are still producing significant emissions: transportation, industry, and fossil fuel supply. There is a continuing need for fossil fuels for jet fuel, heavy-freight movement, and rail and air transport, primarily due to feedstock supply constraints for the production of biofuels. Fuel-switching limitations also exist in the industrial and fossil fuel supply sectors.

Corresponding results for Scenario 8 are shown in Figure 5. In this case, the largest reduction in combustion emissions is 60 per cent lower than the 1990 level, which results in 170 MT in 2050. The premises for this scenario are identical to those of Scenario 8a, except that fossil fuel production projections are consistent with the NEB projections, resulting in much higher production and export of fossil fuels. General trends observed for Scenario 8a also apply to Scenario 8.

Several noteworthy observations arise from an examination of Figure 4. While there is a continually increasing demand for energy-related services from 2011 to 2050, the total energy consumption in 2050 is almost the same as in 2011. There are two principal reasons for this: ongoing energy efficiency improvements, driven by costs associated with increasingly stringent emission reduction targets, and significant shifts from using internal combustion engines and combustion turbines to using electric motors for motive power, particularly in the transportation sector. Conversion efficiencies for electric motors are generally three to four times greater than for combustion technologies, with corresponding reductions in primary energy consumption.

A more qualitative assessment is made of the potential for reducing GHG emissions from non-combustion sources. These emissions are projected to increase from 164 MT in 1990 to 232 MT in 2050 for Scenario 8a. This is compared to 354 MT for the Reference Scenario.

The results from the most aggressive scenario (Scenario 8a) show significant progress on GHG emission reductions, but they fall short of the 80 per cent emission reduction goal. Achieving this may require the use of net-negative emission strategies well before 2050. These could include GHG sequestration with afforestation and reforestation, in addition to using bioenergy with CCS and implementing a comprehensive harvested wood-products program.

The results presented in figures 4 to 6 include the effects of adopting significant energy conservation and efficiency measures, which represent many of the lowest-cost options (including several at negative cost) for reducing GHG emissions from combustion. For example, energy conservation measures account for a large proportion of the demand for space heating in the commercial sector — as much as 60 per cent in 2050, depending on the scenario (and as much as 40 per cent in the residential sector).

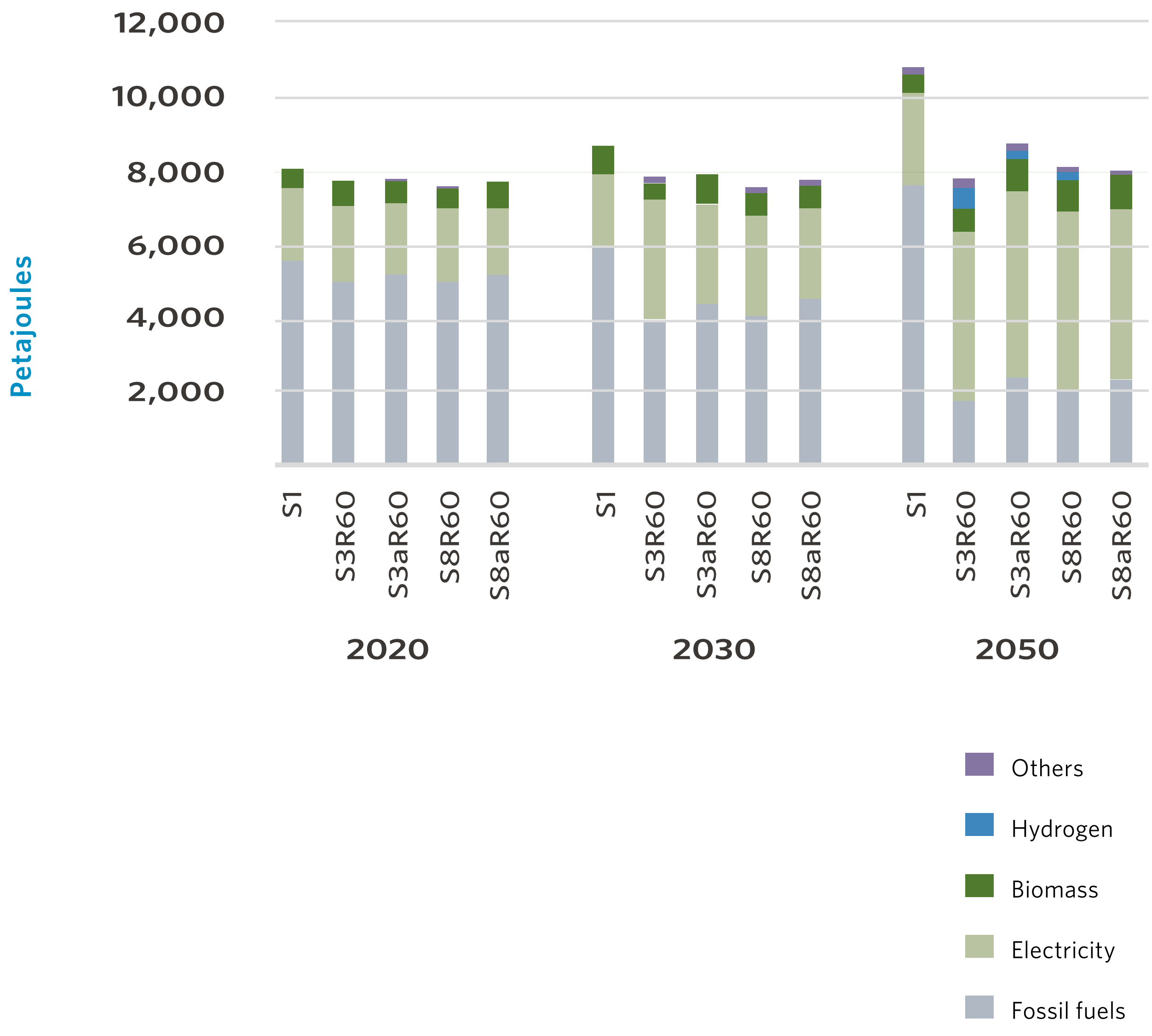


Figure 4: Final energy consumption

Note: Scenario 1 (S1) is the Reference Scenario, with no GHG mitigation. Scenario 3 is for 60 per cent reduction of combustion-based emissions in 2050, based on proven technologies and high production and export of fossil fuels. S3a is the same as S3, except for reduced production and export of fossil fuels. Scenarios 8 and 8a are for 60 per cent emission reductions and include promising but not yet commercially available technologies, such as second-generation biofuels.

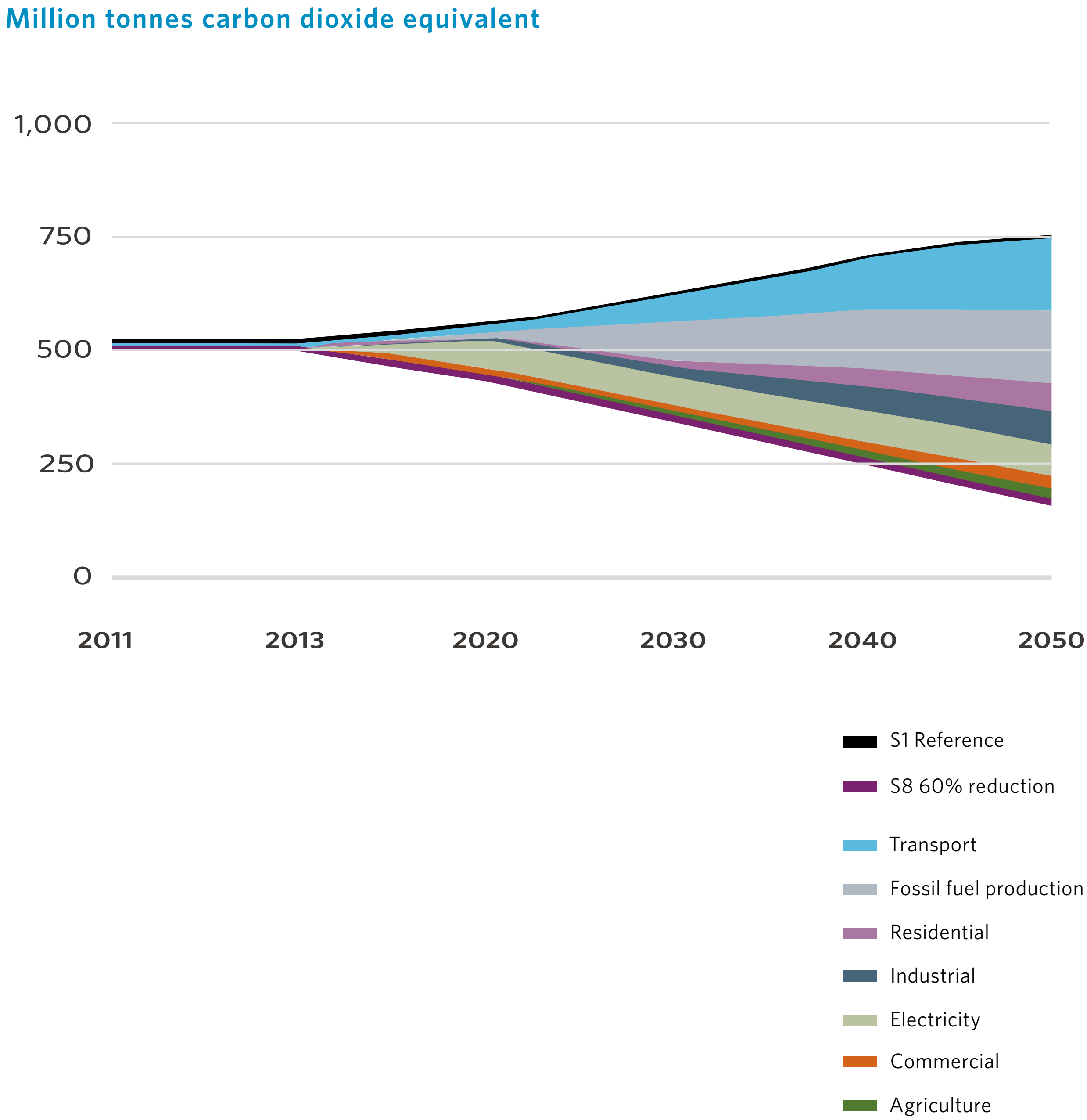


Figure 5a: The reduction in combustion emissions for Scenario 8 relative to Scenario 1 (the Reference Scenario) for achieving a 60 per cent reduction in GHG combustion emissions by 2050, relative to 1990

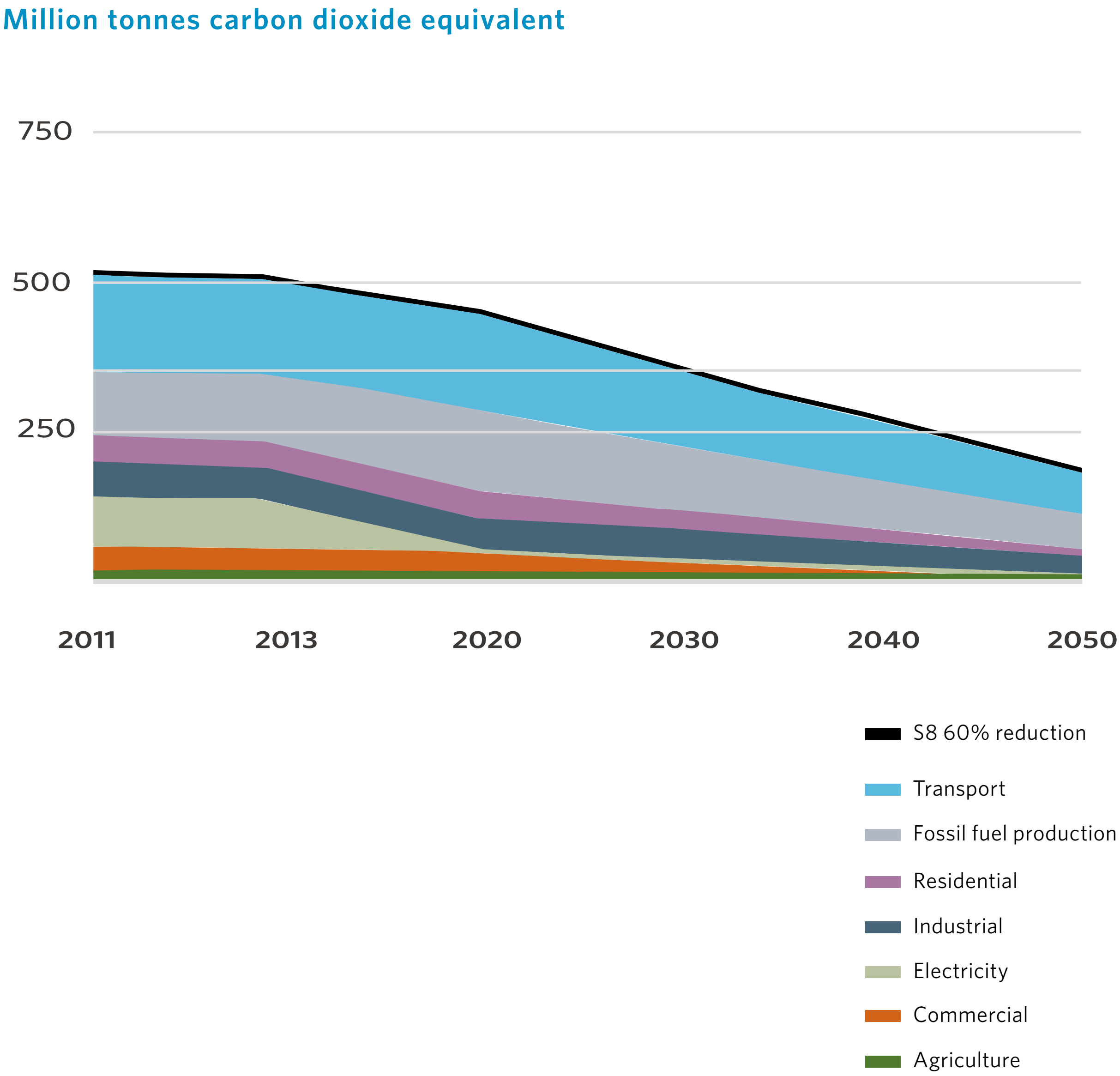


Figure 5b: Projected emissions for each sector to meet a 60 per cent emissions reduction in GHG combustion emissions by 2050, relative to 1990

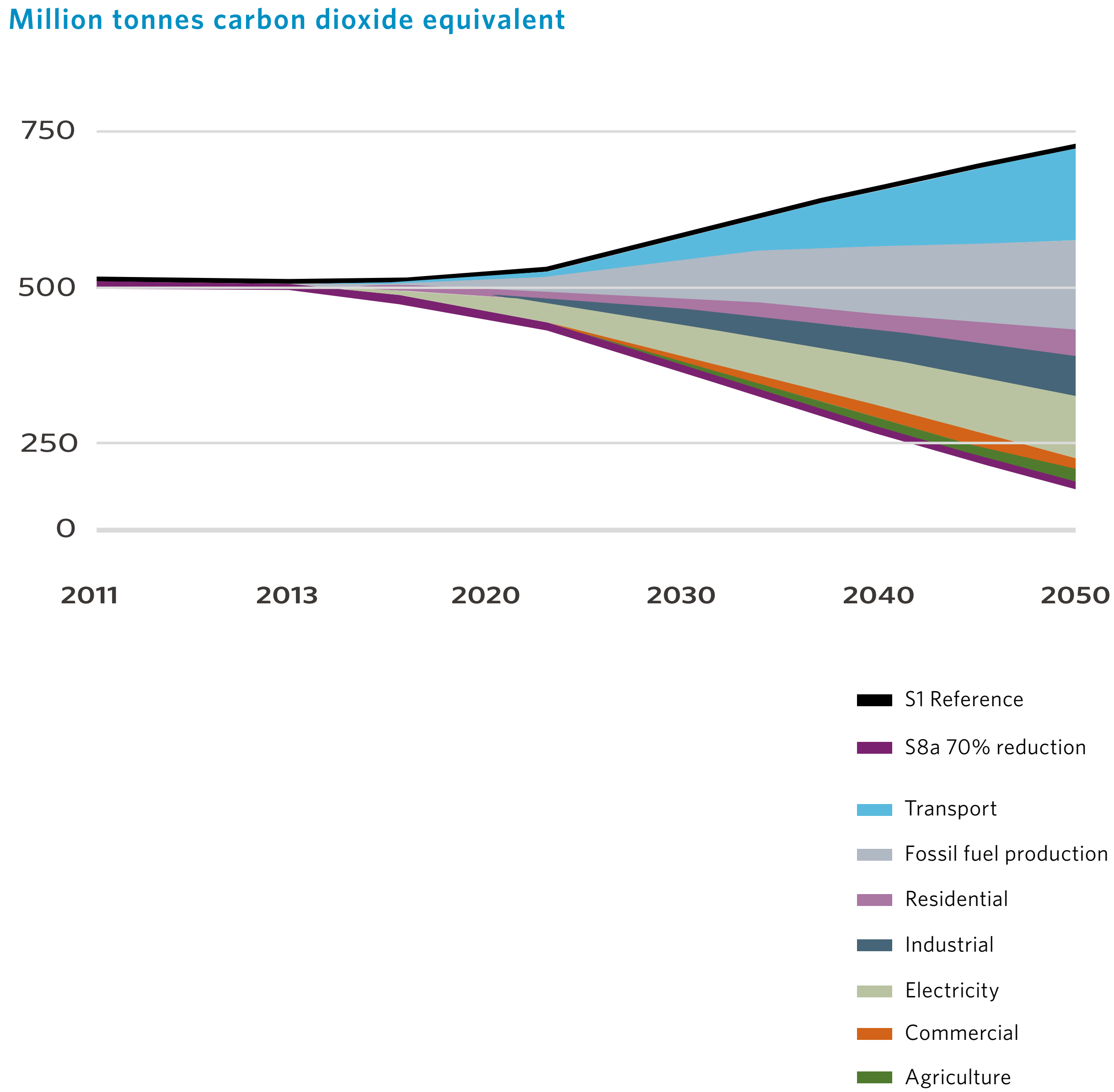


Figure 6a: The reduction in combustion emissions for Scenario 8a, relative to Scenario 1a (no GHG emission constraints) for achieving a 70 per cent reduction in GHG combustion emissions by 2050, relative to 1990

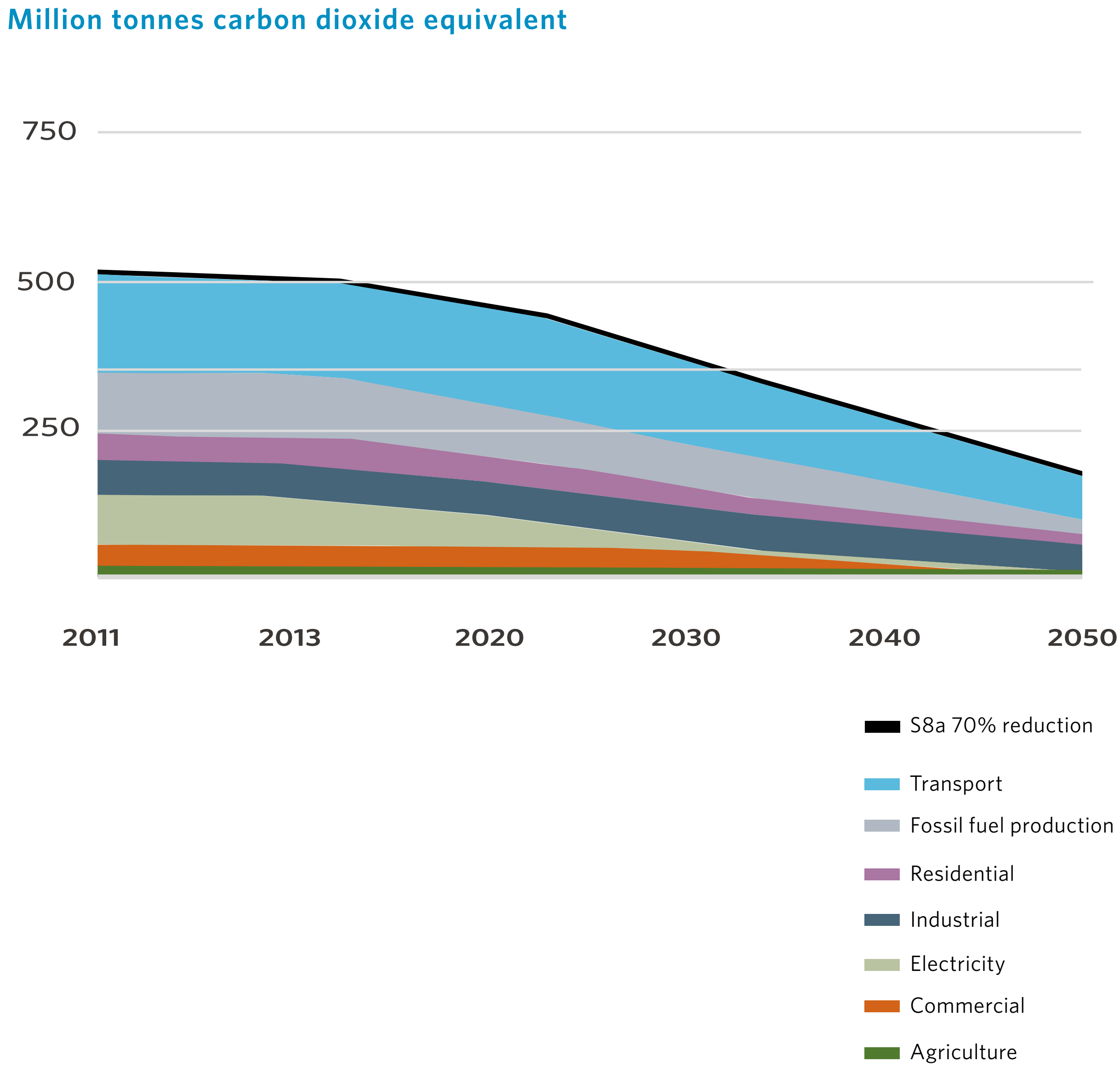


Figure 6b: Projected emissions for each sector to meet the 70 per cent reduction in GHG combustion emissions by 2050, relative to 1990

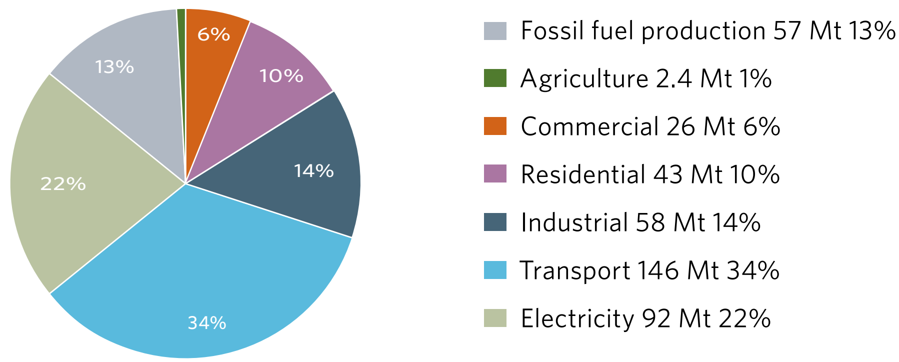
Short-term results

Short-term comparative results for Scenario 8a for reducing combustion emissions between 1990 and 2030 are shown in Figure 7. Total recorded combustion emissions of 425 MT in 1990 increased to 503 MT in 2010. In the absence of concerted action to reduce these emissions, the projection is for a further increase to 618 MT in 2030. By taking the most aggressive action to reduce emissions (Scenario 8a), a reduction from 503 MT in 2010 to 335 MT in 2030 is achieved, corresponding to a 46 per cent reduction relative to 618 MT in the Reference Scenario.

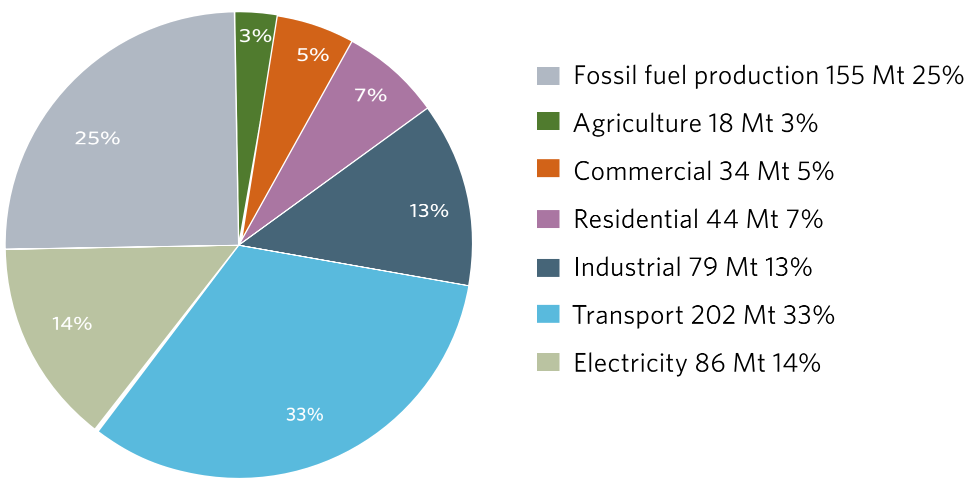
The principal changes in computed results from 2011 to 2030 include the following:

- Progressive reduction in the use of fossil fuels and increasing use of electricity and biomass/biofuels in all five end-use sectors, including, as examples:
  - Increased use of electricity and biofuels in the transportation sector, from three per cent in 2011 to 18 per cent by 2030
  - Increased use of electricity in the residential sector, from 38 per cent in 2011 to 57 per cent in 2030, with increased use of electric boilers, electric water heaters, baseboard heaters and electrically driven heat pumps
  - 45 per cent increase in electricity production between 2011 and 2030, compared to an 18 per cent increase for Scenario 1
- Rapid decarbonization of electricity supply, including the following:
  - 76 per cent increase in hydro generation, with hydro's portion of total electricity generation increasing from 62 per cent in 2011 to 75 per cent in 2030
  - 3.5-fold increase in intermittent renewables generation (dominated by wind), with the portion of total generation increasing from three per cent in 2011 to six per cent in 2030
  - 48 per cent reduction in conventional thermal generation, with the portion of total generation declining from 20 per cent in 2011 to seven per cent in 2030
  - Introduction of biomass-based generation, combined with CCUS by 2030, resulting in net negative emissions, with associated net combustion emissions for electricity production declining from 87 MT in 2011 to 1 MT in 2030
- Additional cost-effective energy efficiency improvements in all sectors

1990 | Total 425 MT



2030 in S1a | Total 618 MT



2030 in S8a (70% reduction) | Total 335 MT

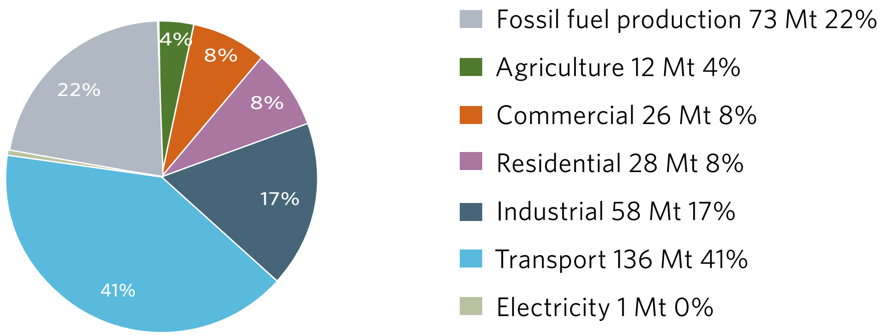


Figure 7: GHG combustion emissions in 1990, compared to projections for low fossil fuel emission Scenarios 1a and 8a in 2030

One of the special attributes of the NATEM optimization model is that it derives marginal costs/tonne of CO_2-equivalent for imposed GHG emission limits. Results for Scenarios 8 and 8a are shown in Figure 8 for a 60 per cent GHG reduction. Marginal costs/tonne vary, depending on the scenario analyzed. They generally exceed $100 per tonne of CO_2-equivalent for combustion emissions in the early years for all scenarios and increase over time to several hundred dollars per tonne (in 2011 dollars).

Figure 8 shows that there is a nearly twofold increase in total marginal costs for Scenario 8 versus Scenario 8a. This reflects the huge costs of reducing emissions from continued fossil fuel production as per the NEB forecast that was incorporated into the project's "high fossil fuel production" scenarios, including Scenario 8. Continued production of these fuels is not likely to be economically feasible unless there is a breakthrough in low-cost extraction with greatly reduced emissions.

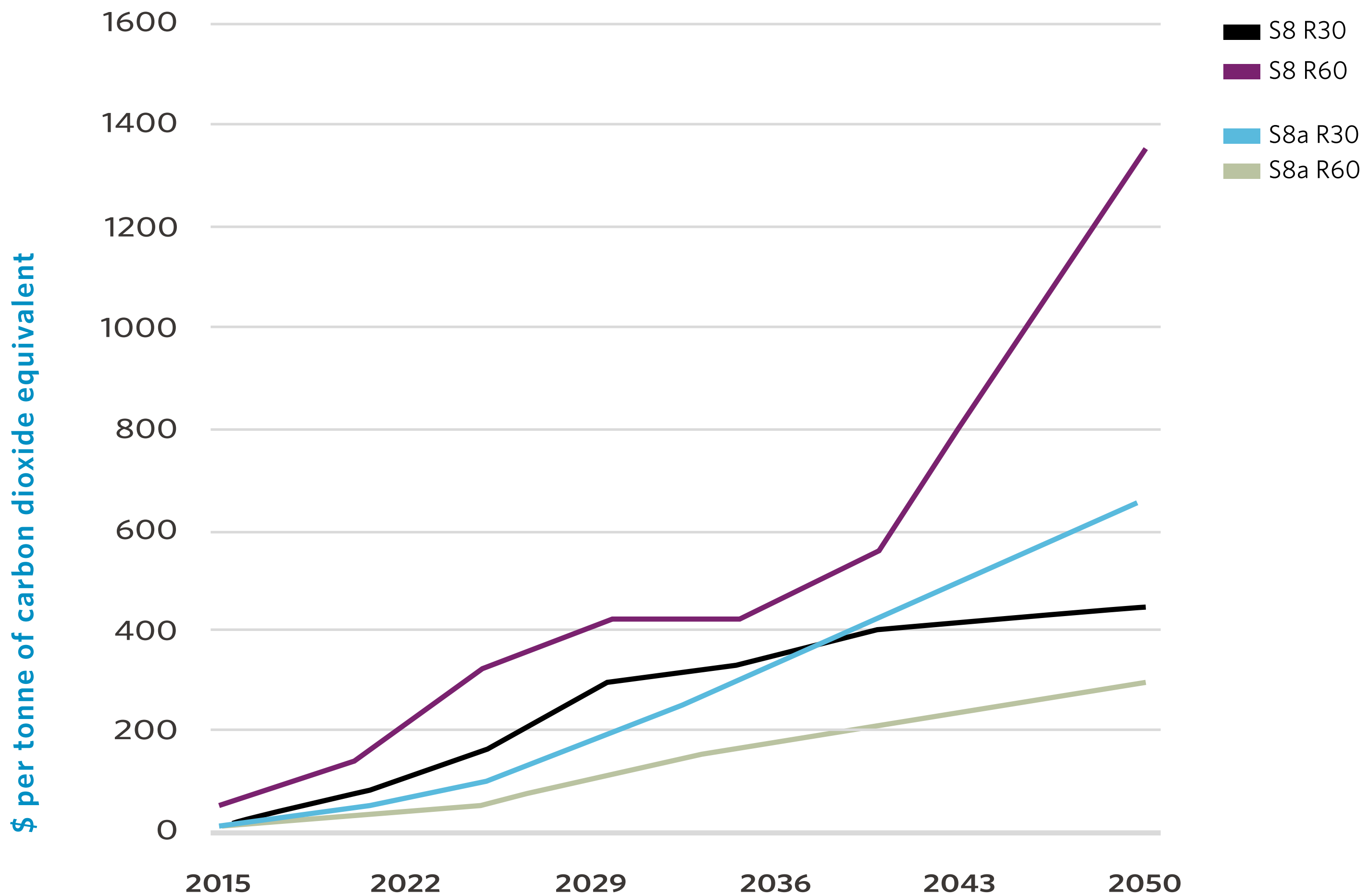


Figure 8: Marginal cost for GHG mitigation for scenarios 8 and 8a

Note: Scenarios 8 and 8a include conventional technologies as well as promising but not yet commercially available technologies, such as second generation biofuels, thermal power with CCS, and bioenergy with CCS, as well as large-scale hydro power in British Columbia. Scenario 8 is based on fossil fuel production from NEB projections, extended to 2050. Scenario 8a is premised on the option of reducing export of fossil fuels by the same ratio as for reduced consumption in Canada. Projections are only shown for 30 per cent and 60 per cent reductions in combustion-based emissions by 2050, relative to 1990.

3. Priorities and where to initiate action

The project highlights the major changes in Canada's existing and future energy infrastructure needed to realize the targeted deep reductions in GHG emissions. The results of the analysis suggest a number of promising pathways to a low-carbon future. In the first 20 years of the simulations (2010 to 2030), the results from the scenario analysis point to a number of opportunities that, if acted upon now, will lead to significant progress toward meeting the GHG emission reduction goals.

- Reduction of dependence on fossil fuels for end uses, mostly by switching to greater use of electricity derived from low-carbon sources or biofuels. This includes, as examples, replacing combustion of fossil fuels for space heating, and hot water and steam production in the residential and commercial sectors, with electric boilers, electric baseboard heaters, electrically driven geothermal and air source heat pumps, and increased use of ambient solar heating. In the transportation sector, the dominant changes indicated by the modelling are toward the use of electric vehicles for passenger cars and light-duty commercial vehicles, the use of biofuels for heavy-duty transport, and selective electrification of rail transport. In the industrial and agricultural sectors, the dominant opportunities involve switching to increased use of electricity and biofuels.

- Reduction of dependence on fossil fuels for electricity production. As shown in the analysis, this is one of the most cost-effective options for quickly reducing combustion emissions. This can be accomplished by replacing existing fossil-fuel fired generating facilities (predominantly coal and natural gas) with low-carbon facilities, and by installing high-voltage interconnections between jurisdictions. The mix to produce the needed electricity supply, whether it be wind, nuclear, hydro, or other sources is scenario dependant and ultimately a function of several factors that were not specifically addressed in the study.

- Enabling interjurisdictional transfers of electricity between provinces and territories that have an abundance of hydroelectric capacity and associated storage with those that do not.

- Ensuring there is adequate electricity supply infrastructure to meet rapidly growing demand for electrification of end uses. This includes not only expanding traditional non-emitting supply infrastructure (hydro, nuclear, wind, etc.) but also taking early actions to ensure that longer-term expansion includes provisions for additional generating capacity at existing and future hydro sites, adding intermittent renewables with corresponding grid strengthening, developing pumped storage sites, combining bioenergy with CCS to produce net negative emissions, and expanding roles for distribution utilities toward integrated local energy management.

- Implementation of a comprehensive program of energy conservation and energy efficiency, especially where such measures directly target reduced dependence on fossil fuels. Significant energy efficiency gains will come with lifestyle modifications, for example. This means changing how we develop and live in urban areas and adopting more efficient buildings, transportation infrastructure and lifestyles.

- Implementation of a coordinated national program for carbon pricing, along with regulations and incentives that support and promote innovative initiatives and developments needed for rising to the GHG mitigation challenge.

These measures and others will define the trajectory for Canada's low-carbon future of 2050. The results of the project provide a glimpse of what that future might look like. It is a future where our energy needs are met by a low- to zero-emitting energy supply infrastructure consisting of a variety of types of power generation installations connected to a robust and smart national energy grid. Electricity flows are not constrained by provincial and territorial boundaries, and agreements are in place so there is optimal use of power generation and energy storage capacity.

In 2050, the use of electricity is pervasive in meeting the energy needs of homes, offices and factories. Families drive electric cars or make use of expanded electric public-transit networks, heavy-duty transport trucks are powered by biofuels (or other new low-carbon technologies), and promising approaches to replacing jet fuel with biojet fuel are becoming commercially viable. Carbon capture and storage techniques ensure that GHG emissions from the burning of fossil fuels are contained. People are conscious of the amount of energy they use, and they use energy in smart ways that are consistent with a culture of conservation.

4. Challenges to be addressed

As the project progressed, a number of significant challenges became apparent. Solutions to address these challenges are not readily available today; however, if these challenges remain unaddressed, achieving deep reductions in GHG emissions will prove exceedingly difficult. Further investigation, assessment and progress are needed in the following areas:

Production of biomass/biofuels. A fourfold increase in the use of biomass/biofuels is projected by 2050, driven by the heavy truck and rail transport sectors. Research and development is needed regarding second-generation biofuels, especially biodiesel.

Heavy freight and rail transport. Remaining challenges in 2050 for achieving reductions in combustion-based emissions include the related issues of high costs for reducing emissions from heavy-duty truck freight and rail transport, and the biomass feedstock supply constraints for biofuel production. Further examination is required of both existing and future options for producing cost-competitive and low-emission fuels for heavy freight and rail transport.

Industrial emissions. Options for reducing

GHG emissions from industrial combustion and non-combustion sources require further investigation and analysis. It is necessary to define additional options for reducing combustion emissions in the industrial sector. Options for reducing industrial process emissions include fuel switching, conservation, process changes, and carbon capture, use and storage.

Oil and natural gas production, upgrading and refining. Extraction, collection, upgrading and refining all result in GHG emissions. In addition to fuel switching, GHG emissions can be reduced through process changes, especially for the in situ extraction and upgrading of heavy bitumen and subsequent refining.

Fugitive emissions. Natural gas that escapes from a variety of sources, such as oil and gas extraction, refining, transportation and distribution is approximately 75 to 95 per cent pure methane, which is much more harmful than CO_2. A comprehensive program of data collection and analysis is needed to assess the full magnitude of fugitive emissions and identify mitigation approaches.

Urban form. Further work is required to assess the extent to which improved urban form can result in reduced overall infrastructure costs and related GHG emissions. Promising approaches include electrified public transit, co-generation, distributed generation, district heating, waste to energy, and local energy storage.

Net-negative emissions. The study examined two possible options for extracting CO_2 from the atmosphere: biomass electricity generation with CCS including the use of CO_2 for enhancing oil recovery, and increased use of wood products for carbon retention in buildings. The study results showed that the benefits from the biomass/CCS combination would be constrained by biomass feedstock limitations. The retention of carbon in buildings could potentially produce a 40 MT CO_2 credit in 2050.

This list of areas requiring further study is not exhaustive; rather, it highlights several areas that are crucial to achieving the 80 per cent reduction goal. Work on these areas is already underway in many parts of Canada and in other countries.

5. Concluding comments

The project has provided an innovative and rigorous analysis of the potential for deep reductions in Canadian GHG emissions. It identifies promising and implementable low-GHG options and pathways for Canada, and it shows the least costly ways to achieve GHG reductions for combustion emissions. The deep-reduction pathways are challenging and involve extensive energy conservation and efficiency measures, major restructuring of our energy infrastructure, deployment of promising but not yet commercially available technologies, and fundamental changes in how people think about and use energy. The energy options that must be implemented to achieve deep GHG reductions (reduced use of fossil fuels for end uses, decarbonization of electricity supply, and increasing use of biomass/biofuels) all result in developments between now and 2050 that present formidable challenges. The results from the project cast considerable doubt about the timely availability of technology and associated infrastructure; however, the greatest challenge may not be technical or even economic as much as political and social/cultural. Deep GHG reductions, therefore, will affect all Canadians and will necessarily involve changes in lifestyle, some of which were partially studied in Scenario 4, which includes assumptions about improved urban form. The project results also speak to a requirement for carbon pricing and supporting regulation. The accomplishment of the societal transformations involved in reducing GHG emissions by 80 per cent or more will require leadership from all sectors of society, including government, industry and non-profit organizations, and will require all Canadians to develop a widely shared vision of low-carbon lifestyles and energy systems.

The challenge does not come without opportunity.

Canada is positioned to be one of the very few countries that can produce emissions-free electricity at a globally competitive cost. Opportunities will arise for the manufacturing of energy-intensive products for export, especially from Canadian jurisdictions that can produce low-cost, emissions-free electricity. Electricity exports to the U.S. could increase and could include the sale of "dependable capacity" to selected neighbouring American jurisdictions.
With the greatly enhanced potential role for the use of biomass and biofuels, both the forestry and agricultural sectors would see opportunity in the provision of energy commodities (biomass and both first- and second-generation biofuels) and in carbon retention, including afforestation, improved forest management, and the production of harvested wood products.

For those sectors involved in the production, processing and transport of fossil fuels, opportunities will open for those who find ways to use these products with greatly reduced emissions using cost-effective techniques for carbon capture, use and storage or for producing low-maintenance, carbon-based storage products.

The results of the project provide insights into Canada's unique position regarding GHG reduction options and pathways, and can be used to inform national dialogue on strategies needed to achieve deep emission reductions. Our future will be determined by the choices we make today about the use of energy and the reduction of GHG emissions. The open and frank discussion this report engenders can lead to meaningful progress and build confidence that Canada can work in harmony internally and with other nations to restore the health and resiliency of the planet's climate system.